COIN-OR: Software Tools for Implementing Custom Solvers

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Agenda

- **Overview of COIN-OR**
- Overview of COIN-OR branch, cut, and price toolbox
  - BCP
  - OSI
  - CGL
  - CLP
  - VOL
- Developing an application
  - Basic concepts
  - Design of BCP
  - User API
- Example

What is COIN-OR?

- The COIN-OR Project
  - A consortium of researchers in both industry and academia dedicated to improving the state of computational research in OR.
  - An initiative promoting the development and use of interoperable, open-source software for operations research.
  - Soon to become a non-profit corporation known as the COIN-OR Foundation
- The COIN-OR Repository
  - A library of interoperable software tools for building optimization codes, as well as a few stand alone packages.
  - A venue for peer review of OR software tools.
  - A development platform for open source projects, including a CVS repository.

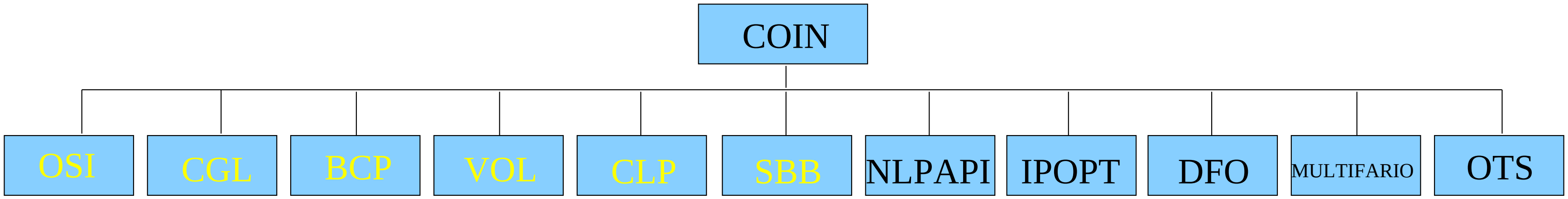
What is Open Source Development?

- *Open source development* is a coding paradigm in which development is done in a cooperative and distributed fashion.
- Strictly speaking, an open source license must satisfy the requirements of the *Open Source Definition*.
- A license cannot call itself "open source" until it is approved by the Open Source Initiative.
- Basic properties of an open source license
  - Access to source code.
  - The right to redistribute.
  - The right to modify.
- The license may require that modifications also be kept open.

Our Agenda

- Accelerate the pace of research in computational OR.
  - Reuse instead of reinvent.
  - Reduce development time and increase robustness.
  - Increase interoperability (standards and interfaces).
- Provide for software what the open literature provides for theory.
  - Peer review of software.
  - Free distribution of ideas.
  - Adherence to the principles of good scientific research.
- Define standards and interfaces that allow software components to interoperate.
- Increase synergy between various development projects.
- Provide robust, open-source tools for practitioners.

Components of the COIN-OR Library



- Branch, cut, price toolbox
  - OSI: Open Solver Interface
  - CGL: Cut Generator Library
  - BCP: Branch, Cut, and Price Library
  - VOL: Volume Algorithm
  - CLP: COIN-OR LP Solver
  - SBB: Simple Branch and Bound
  - COIN: COIN-OR Utility Library
- Stand-alone components
  - IPOPT: Interior Point Optimization
  - NLPAPI: Nonlinear Solver interface
  - DFO: Derivative Free Optimization
  - MULTIFARIO: Solution Manifolds
  - OTS: Open Tabu Search

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BCP Overview

- Concept: Provide a *framework* in which the user has only to define the core relaxation, along with classes of dynamically generated variables and constraints.
  - Branch and bound ⇒ core relaxation only
  - Branch and cut ⇒ core relaxation plus constraints
  - Branch and price ⇒ core relaxation plus variables
  - Branch, cut, and price ⇒ the whole caboodle
- Existing frameworks
  - SYMPHONY (parallel, C)
  - COIN/BCP (parallel, C++)
  - ABACUS (sequential, C++)
- Components
  - Framework (BCP)
  - LP Solver (OSI)
  - Cut Generator (CGL)
  - Utilities (COIN)

OSI Overview

Uniform interface to LP solvers, including:

- CLP (COIN-OR)
- CPLEX (ILOG)
- DyLP (BonsaiG LP Solver)
- GLPK (GNU LP Kit)
- OSL (IBM)
- SoPlex (Konrad-Zuse-Zentrum für Informationstechnik Berlin)
- Volume (COIN-OR)
- XPRESS (Dash Optimization)
- MOSEK (under construction)

CGL Overview

- Collection of cut generation routines integrated with OSI.
- Intended to provide robust implementations, including computational tricks not usually published.
- Currently includes:
  - Simple rounding cut
  - Gomory cut
  - Knapsack cover cut
  - Rudimentary lift-and-project cut
  - Odd hole cut
  - Probing cut

VOL Overview

- Generalized subgradient optimization algorithm.
- Compatible with branch, cut, and price:
  - provides approximate primal and dual solutions,
  - provides a valid lower bound (feasible dual solution), and
  - provides a method for warm starting.

CLP Overview

- A full-featured, open source LP solver.
- Has interfaces for primal, dual, and network simplex.
- Can be accessed through the OSI.
- Reasonably robust and fast.

SBB Overview

- A lightweight generic MIP solver.
- Uses OSI to solve the LP relaxations.
- Uses CGL to generate cuts.
- Optimized for CLP.

COIN Utility Library Overview

- Contains classes for
  - Storage and manipulation of sparse vectors and matrices.
  - Factorization of sparse matrices.
  - Storage of solver warm start information.
  - Message handling.
  - Reading/writing of MPS files.
  - Other utilities (simultaneous sorting, timing, . . .).
- These are the classes common to many of the other algorithms.

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Basic Concepts

- We consider problem P:

$$\begin{array}{lrcll} \min & c^T x & & & \\ \text{s.t.} & Ax & \leq & b & \\ & x_i & \in & \mathbb{Z} & \forall\, i \in I \end{array}$$

  where $A \in \mathbb{R}^{m \times n}$, $b \in \mathbb{R}^m$, $c \in \mathbb{R}^n$.

- Let $\mathcal{P} = \text{conv}\{x \in \mathbb{R}^n : Ax \leq b,\ x_i \in \mathbb{Z}\ \forall\, i \in I\}$.

- Basic Algorithmic Approach
  - Use *LP relaxations* to produce *lower bounds*.
  - *Branch* using hyperplanes.
  - The LP relaxations are built up from a core relaxation with dynamically generated *objects* (variables and constraints).

Object Generation

- The efficiency of BCP depends heavily on the size (number of rows and columns) and tightness of the LP relaxations.
- Tradeoff
  - Small LP relaxations ⇒ faster LP solution.
  - Big LP relaxations ⇒ better bounds.
- The goal is to keep relaxations small while not sacrificing bound quality.
- We must be able to easily move constraints and variables in and out of the *active* set.
- This means dynamic generation and deletion.
- Defining a class of objects consists of defining methods for
  - generating new objects, given the primal/dual solution to the current LP relaxation,
  - representing the object (for storage and/or sharing), and
  - adding objects to a given LP relaxation.

Getting Started

- The source can be obtained from `www.coin-or.org` as "tarball" or using CVS.
- Platforms/Requirements
  - Linux, gcc 2.95.3/2.96RH/3.2/3.3
  - Windows, Visual C++, CygWin make (untested)
  - Sun Solaris, gcc 2.95.3/3.2 or SunWorkshop C++
  - AIX gcc 2.95.3/3.3
  - Mac OS X
- Editing the Makefiles
  - `Makefile.location`
  - `Makefile.<operating system>`
- Make the necessary libraries. They'll be installed in `${CoinDir}/lib`.
  - Change to appropriate directory and type `make`.

BCP Modules

- The BCP library is divided into three basic modules:
  - **Tree Manager** Controls overall execution by maintaining the search tree and dispatching subproblems to the node processors.
  - **Node Processor** Perform processing and branching operations.
  - **Object Generation** Generate objects (cuts and/or variables).
- The division into separate modules is what allows the code to be parallelizable.

The User API

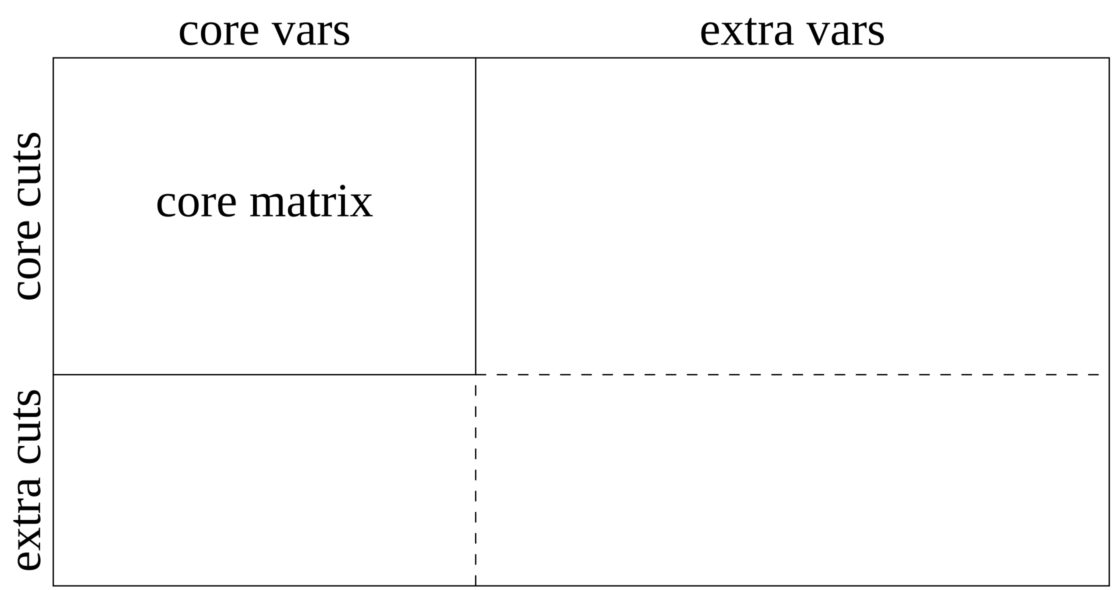
- The user API is implemented via a C++ class hierarchy.
- To develop an application, the user must derive the appropriate classes override the appropriate methods.
- Classes for customizing the behavior of the modules
  - BCP_tm_user
  - BCP_lp_user
  - BCP_cg_user
  - BCP_vg_user
- Classes for defining user objects
  - BCP_cut
  - BCP_var
  - BCP_solution
- Allowing BCP to create instances of the user classes.
  - The user must derive the class USER_initialize.
  - The function BCP_user_init() returns an instance of the derived initializer class.

Objects in BCP

- Most application-specific methods are related to handling of objects.
- Since representation is independent of the current LP, the user must define methods to add objects to a given subproblem.
- For parallel execution, the objects need to be packed into (and unpacked from) a buffer.
- Object Types
  - Core objects are objects that are active in *every* subproblem (BCP_xxx_core).
  - Indexed objects are extra objects that can be uniquely identified by an index (such as the edges of a graph) (BCP_xxx_indexed).
  - Algorithmic objects are extra objects that have an abstract representation (BCP_xxx_algo).

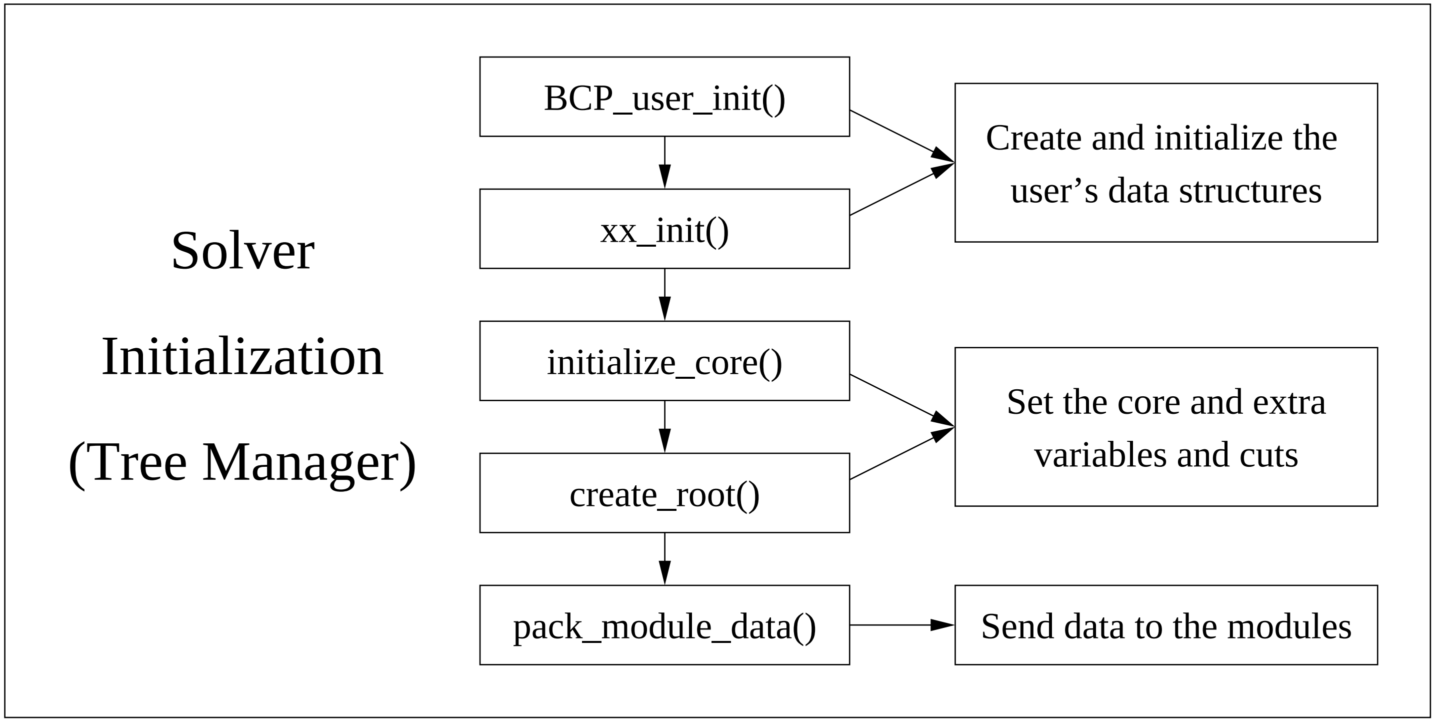
Forming the LP Relaxations in BCP

The current LP relaxation looks like this:

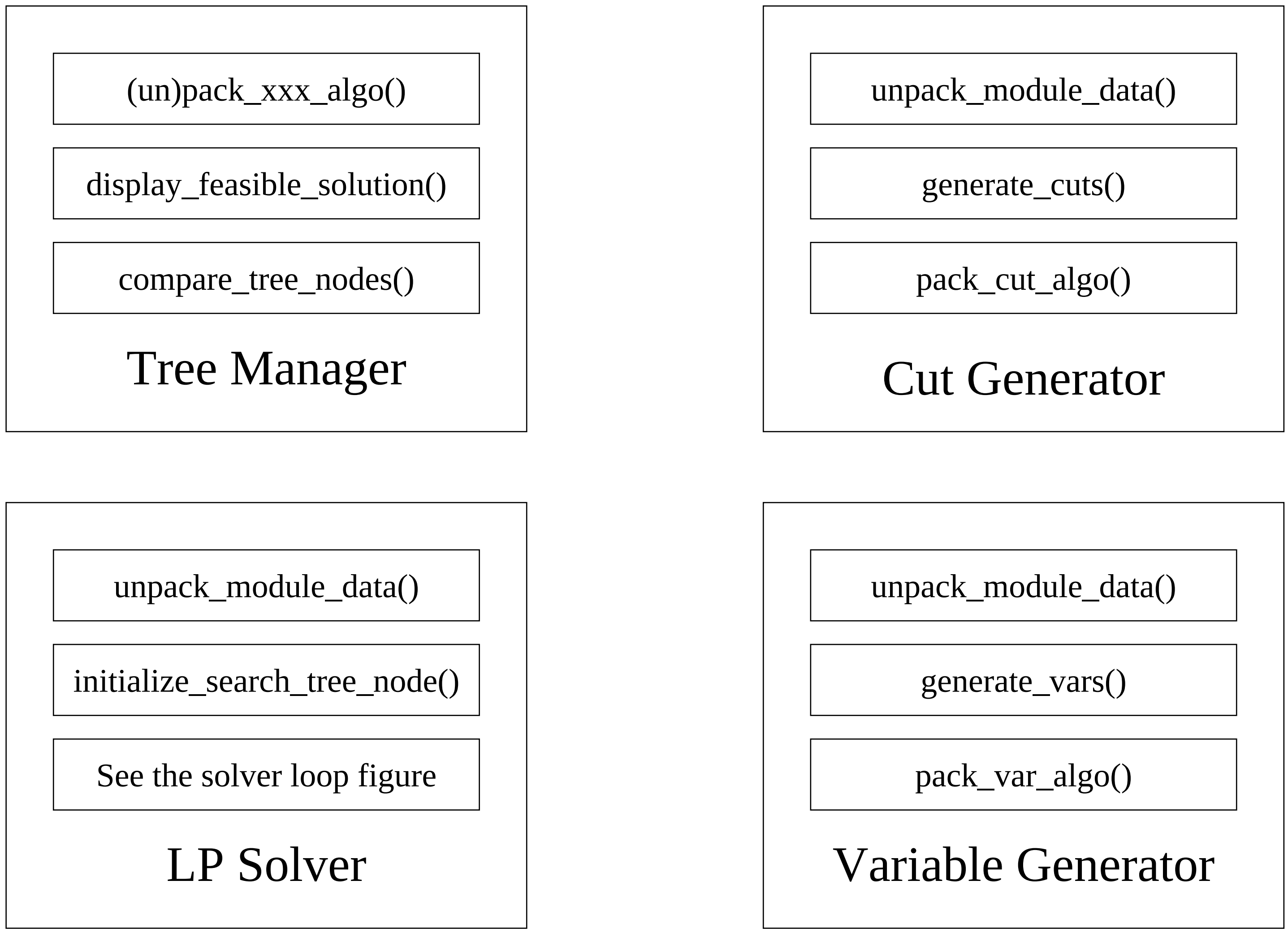


Reason for this split: efficiency.

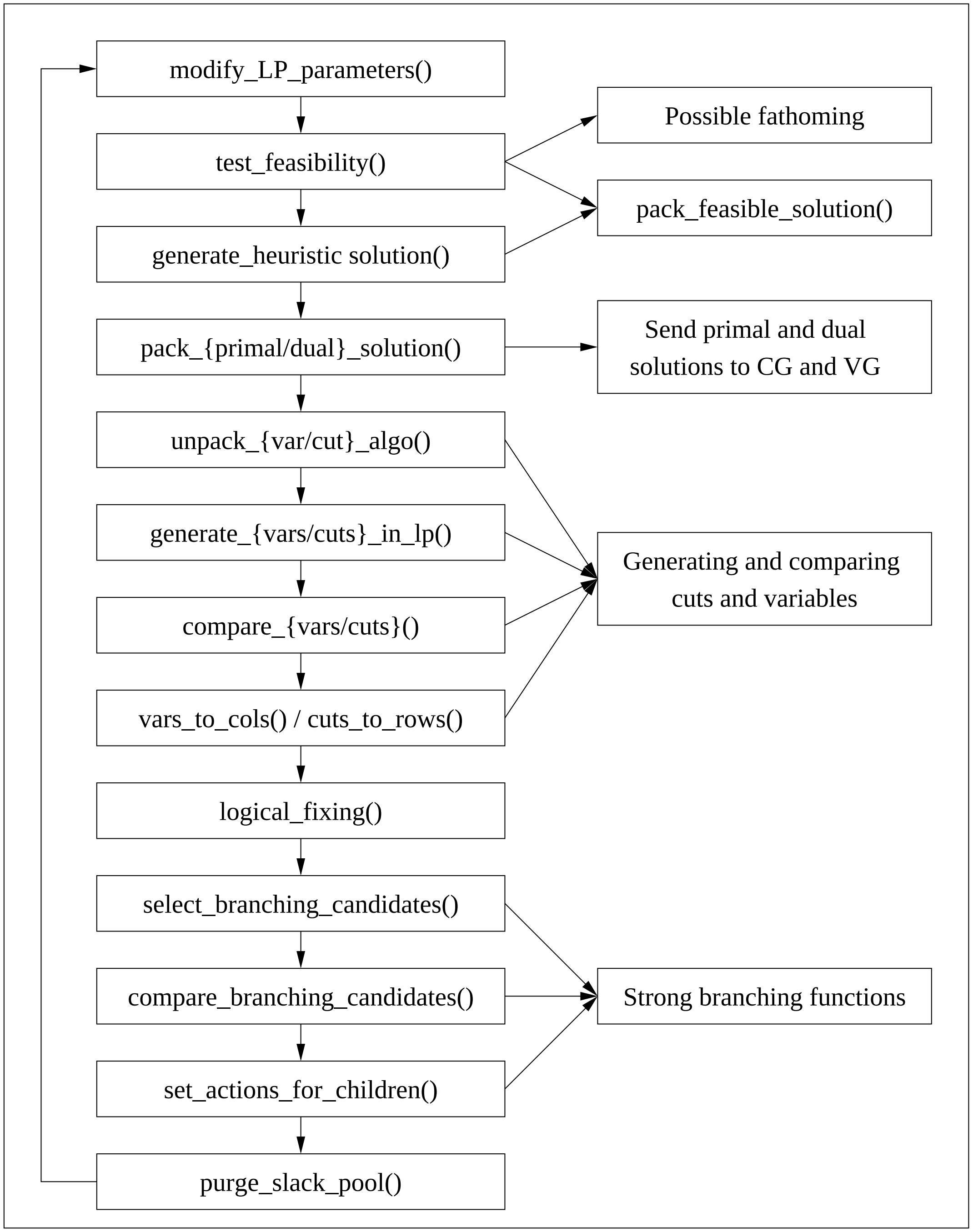
BCP Methods: Initialization



BCP Methods: Steady State



BCP Methods: Node Processing Loop



Parameters and using the finished code

- Create a parameter file
- Run your code with the parameter file name as an argument (command line switches will be added).
- `BCP_` for BCP's parameters
- Defined and documented in BCP_tm_par, BCP_lp_par, etc.
- Helper class for creating your parameters.
- Output controlled by verbosity parameters.

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Example: Uncapacitated Facility Location

- Data
  - a set N of facilities and a set M of clients,
  - transportation cost c_{ij} to service client i from depot j,
  - fixed cost f_j for using depot j, and
  - the demand of d_i of client i.
- Variables
  - x_{ij} is the amount of the demand for client i satisfied from depot j
  - y_j is 1 if the depot is used, 0 otherwise

$$
\begin{aligned}
\min \sum_{i \in M} \sum_{j \in N} \frac{c_{ij}}{d_i} x_{ij} + \sum_{j \in N} f_j y_j \\
s.t. \quad \sum_{j \in N} x_{ij} = d_i & \quad \forall i \in M, \\
\sum_{i \in M} x_{ij} \leq (\sum_{i \in M} d_i) y_j & \quad \forall j \in N, \\
y_j \in \{0, 1\} & \quad \forall j \in N \\
0 \leq x_{ij} \leq d_i & \quad \forall i \in M, j \in N
\end{aligned}
$$

UFL: Solution Approach

- The code for this example is available at

  http://sagan.ie.lehigh.edu/coin/uflBCP.tar.gz

- We use a simple branch and cut scheme.
- We dynamically generate the following class disaggregated logical cuts

$$x_{ij} <= d_j y_j, \ \forall i \in M, j \in N \tag{1}$$

- These can be generated by complete enumeration.
- The indices i and j uniquely identify the cut., so we will use this to create the packed form.
- The core relaxation will consist of the LP relaxation.

UFL: User classes

User classes and methods

- UFL_init
  - `tm_init()`
  - `lp_init()`
- UFL_lp
  - `unpack_module_data()`
  - `pack_cut_algo()`
  - `unpack_cut_algo()`
  - `generate_cuts_in_lp()`
  - `cuts_to_rows()`
- UFL_tm
  - `read_data()`
  - `initialize_core()`
  - `pack_module_data()`
- UFL_cut

UFL: Initialization Methods

```
USER_initialize * BCP_user_init()
{
   return new UFL_init;
}

BCP_lp_user *
UFL_init::lp_init(BCP_lp_prob& p)
{
   return new UFL_lp;
}

BCP_tm_user * UFL_init::tm_init(BCP_tm_prob& p, const int argnum,
                                const char * const * arglist)
{
   UFL_tm* tm = new UFL_tm;
   tm->tm_par.read_from_file(arglist[1]);
   tm->lp_par.read_from_file(arglist[1]);
   return tm;
}
```

BCP Buffers

- One construct that is pervasive in BCP is the BCP_buffer.
- A BCP_buffer consists of a character string into which data can be packed for storage or communication (parallel code).
- The usual way of adding data to a buffer is to use the pack() method.
- The pack method returns a reference to the buffer, so that multiple calls to pack() can be strung together.
- To pack integers i and j into a buffer and then unpack from the same buffer again, the call would be:

```
int i = 0, j = 0;
BCP_buffer buf;

buf.pack(i).pack(j);
buf.unpack(i).unpack(j);
```

UFL: Module Data

- Because BCP is a parallel code, there is no shared between modules.
- The pack_module_data() and unpack_module_data() methods allow instance data to be broadcast to other modules.
- In the UFL, the data to be broadcast consists of the number of facilities (N), the number of clients (N), and the demands.
- Here is what the pack and unpack methods look like.

```
void UFL_tm::pack_module_data(BCP_buffer& buf, BCP_process_t pty
{
  lp_par.pack(buf);
  buf.pack(M).pack(N).pack(demand,M);
}

void UFL_lp::unpack_module_data(BCP_buffer& buf) {
  lp_par.unpack(buf);
  buf.unpack(M).unpack(N).unpack(demand,M).unpack(capacity,N);
}
```

UFL: Initializing the Core

- The core is specified as an instance of the BCP_lp_relax class, which can be constructed from
  - either a vector of BCP_rows or BCP_cols, and
  - a set of rim vectors.
- In the initialize_core() method, the user must also construct a vector of BCP_cut_core and BCP_var_core objects.

UFL: Initializing the Solver Interface

- In the BCP_lp_user class, we must initialize the solver interface to let BCP know what solver we want to use.
- Here is what that looks like:

```
OsiSolverInterface* UFL_lp::initialize_solver_interface(){
#if COIN_USE_OSL
  OsiOslSolverInterface* si = new OsiOslSolverInterface();
#endif
#if COIN_USE_CPX
  OsiCpxSolverInterface* si = new OsiCpxSolverInterface();
#endif
#if COIN_USE_CLP
  OsiClpSolverInterface* si = new OsiClpSolverInterface();
#endif
  return si;
}
```

UFL: Cut Class

```
class UFL_cut : public BCP_cut_algo{
public:
  int i,j;
public:
  UFL_cut(int ii, int jj):
    BCP_cut_algo(-1 * INF, 0.0), i(ii), j(jj) {
  }
  UFL_cut(BCP_buffer& buf):
    BCP_cut_algo(-1 * INF, 0.0), i(0), j(0) {
    buf.unpack(i).unpack(j);
  }
  void pack(BCP_buffer& buf) const;
};

inline void UFL_cut::pack(BCP_buffer& buf) const{
  buf.pack(i).pack(j);
}
```

UFL: Generating Cuts

- To find violated cuts, we simply enumerate, as in this code snippet.

```
double violation;
vector< pair<int,int> > cut_v;
map<double,int> cut_violation; //map keeps violations sorted
map<double,int>::reverse_iterator it;

for (i = 0; i < M; i++){
   for (j = 0; j < N; j++){
      xind = xindex(i,j);
      yind = yindex(j);
      violation = lpres.x()[xind]-(demand[i]*lpres.x()[yind]);
      if (violation > tolerance){
 cut_v.push_back(make_pair(i,j));
 cut_violation.insert(make_pair(violation,cutindex++));
      }
   }
}
```

UFL: Constructing Cuts

- Next, we pass the most violated cuts back to BCP.

```
//Add the xxx most violated ones.
maxcuts = min((int)cut_v.size(),
              lp_par.entry(UFL_lp_par::UFL_maxcuts_iteration));
it = cut_violation.rbegin();
while(newcuts<maxcuts){
   cutindex = it->second;
   violation = it->first;
   new_cuts.push_back(new UFL_cut(cut_v[cutindex].first,
                                  cut_v[cutindex].second));
   newcuts++;
   it++;
}
```

UFL: Adding Cuts to the LP

- Here is the cuts_to_rows function that actually generates the rows to be added to the LP relaxation.

```
void UFL_lp::cuts_to_rows(const BCP_vec<BCP_var*>& vars,
  BCP_vec<BCP_cut*>& cuts,
  BCP_vec<BCP_row*>& rows,
  const BCP_lp_result& lpres,
  BCP_object_origin origin, bool allow_multiple){
   const int cutnum = cuts.size();
   rows.reserve(cutnum);
   for (int c = 0; c < cutnum; ++c) {
      UFL_cut* mcut = dynamic_cast<const UFL_cut*>(cuts[c]);
      if (mcut != 0){
         CoinPackedVector cut;
         cut.insert(xindex(mcut->i,mcut->j), 1.0);
         cut.insert(yindex(mcut->j), -1.0 * demand[mcut->i]);
         rows.push_back(new BCP_row(cut,-1.0 * INF, 0.0));
      }
   }
}
```

Resources

- Documentation
  - There is a user's manual for BCP, but it is out of date.
  - The most current documentation is in the source code—don't be afraid to use it.
- Other resources
  - There are several mailing lists on which to post questions and we make an effort to answer quickly.
  - Also, there is a lot of good info at `www.coin-or.org`.
  - There are some basic tutorials and other information, including the example you saw today at `sagan.ie.lehigh.edu/coin/`.
- There is a user's meeting Monday at 12:00 in International Ballroom A.
- There are three other sessions revolving around COIN software, including a tutorial on OSI.

Final advice

Use the source, Luke...

...and feel free to ask questions either by email or on the discussion list.